



US 20080024792A1

(19) **United States**

(12) **Patent Application Publication**  
**Pendry et al.**

(10) **Pub. No.: US 2008/0024792 A1**

(43) **Pub. Date: Jan. 31, 2008**

(54) **ELECTROMAGNETIC CLOAKING METHOD**

**Publication Classification**

(76) Inventors: **John Pendry**, London (GB);  
**David Smith**, Durham, NC (US);  
**David Schurig**, Durham, NC (US)

(51) **Int. Cl.**  
**G01B 11/24** (2006.01)

(52) **U.S. Cl.** ..... **356/602**

Correspondence Address:  
**HAMILTON, BROOK, SMITH & REYNOLDS,**  
**P.C.**  
**530 VIRGINIA ROAD, P.O. BOX 9133**  
**CONCORD, MA 01742-9133**

(57) **ABSTRACT**

A method of constructing a concealing volume comprises constructing a plurality of concealing volume elements around a concealable volume. Each concealing volume element has a material parameter arranged to direct a propagating wave around the concealable volume.

(21) Appl. No.: **11/459,728**

(22) Filed: **Jul. 25, 2006**

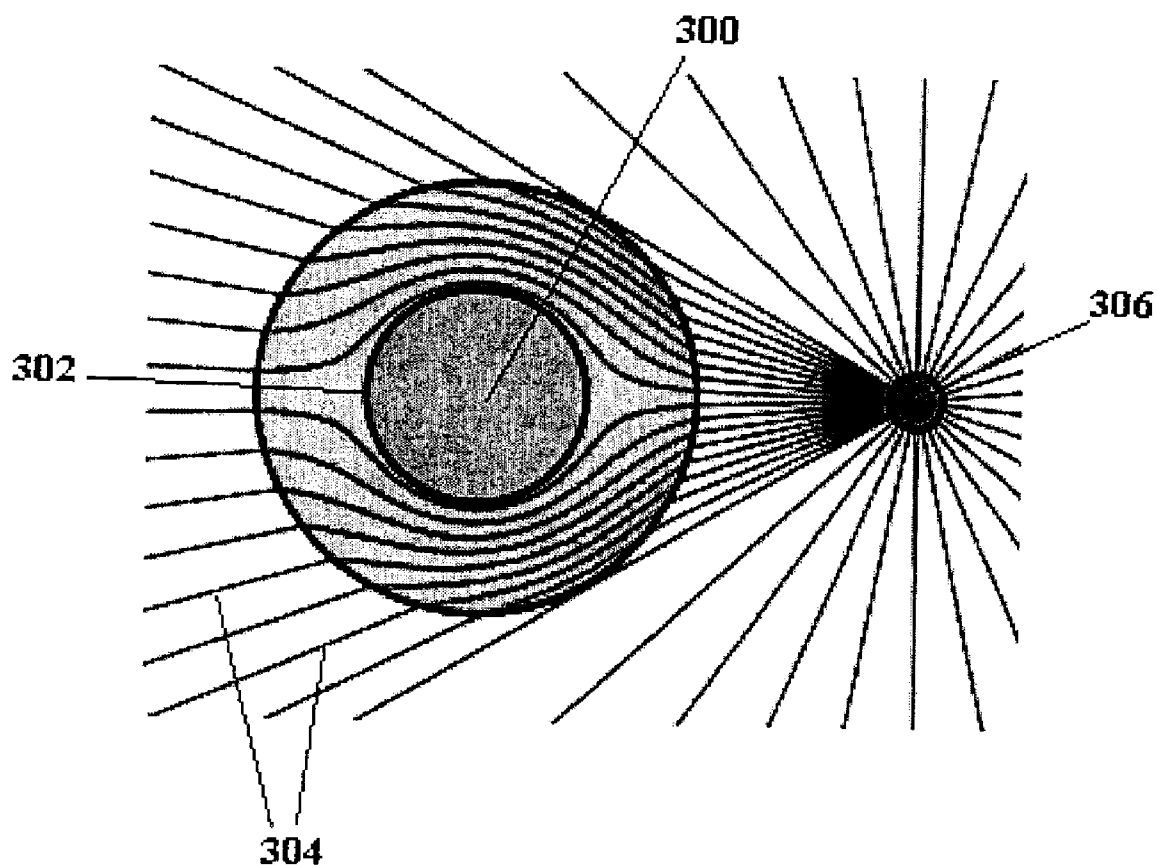


Fig 1

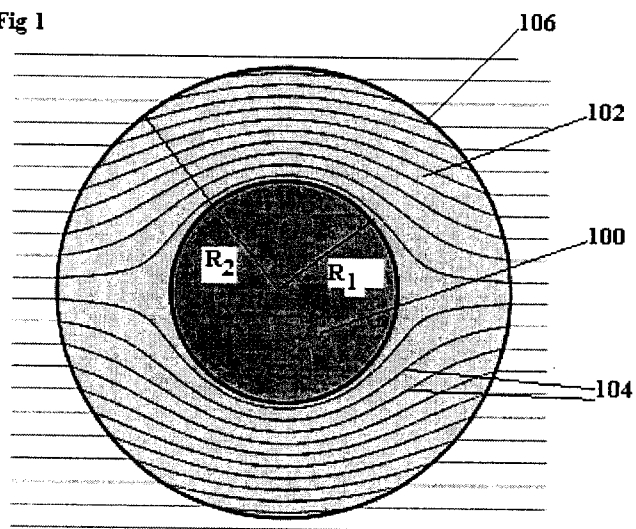


Fig 2a

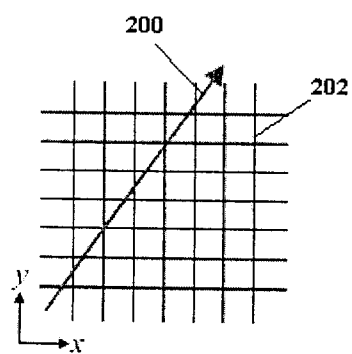
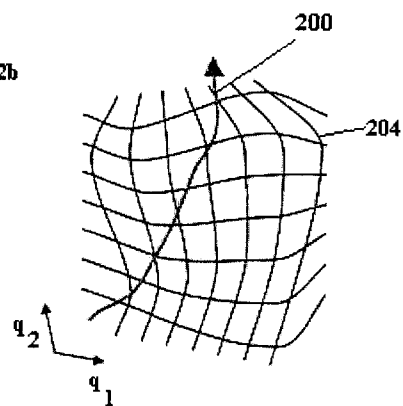


Fig 2b



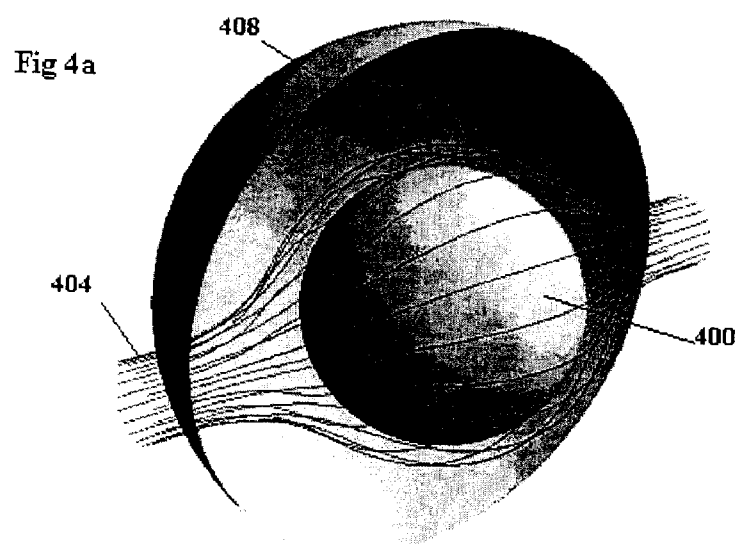
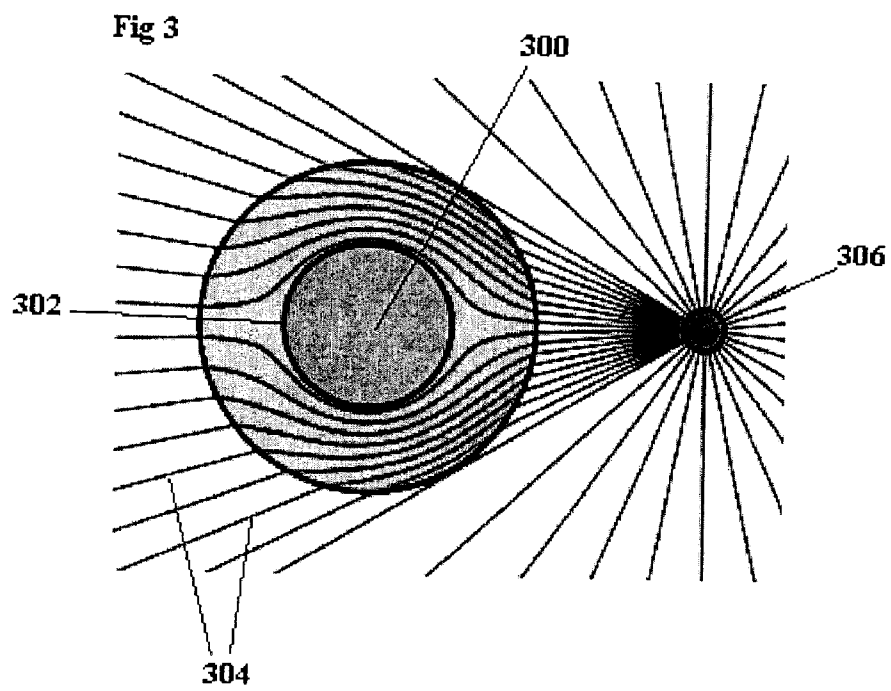


Fig 4b

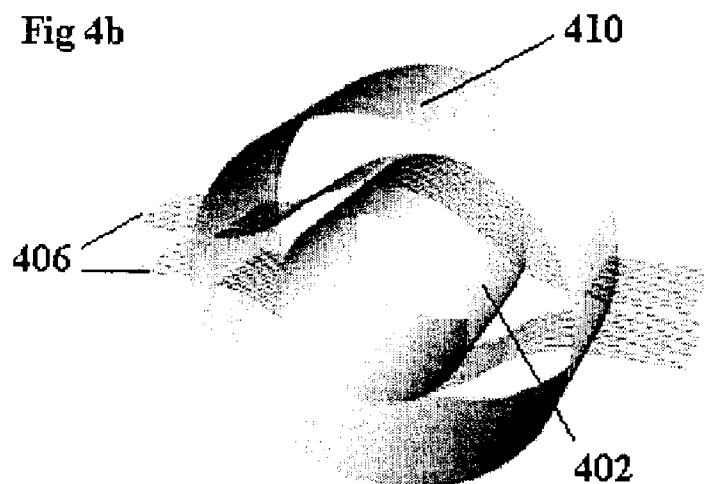
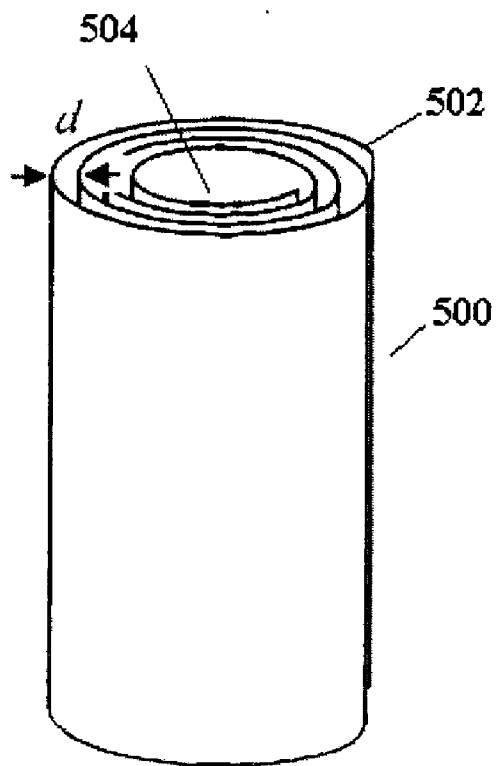
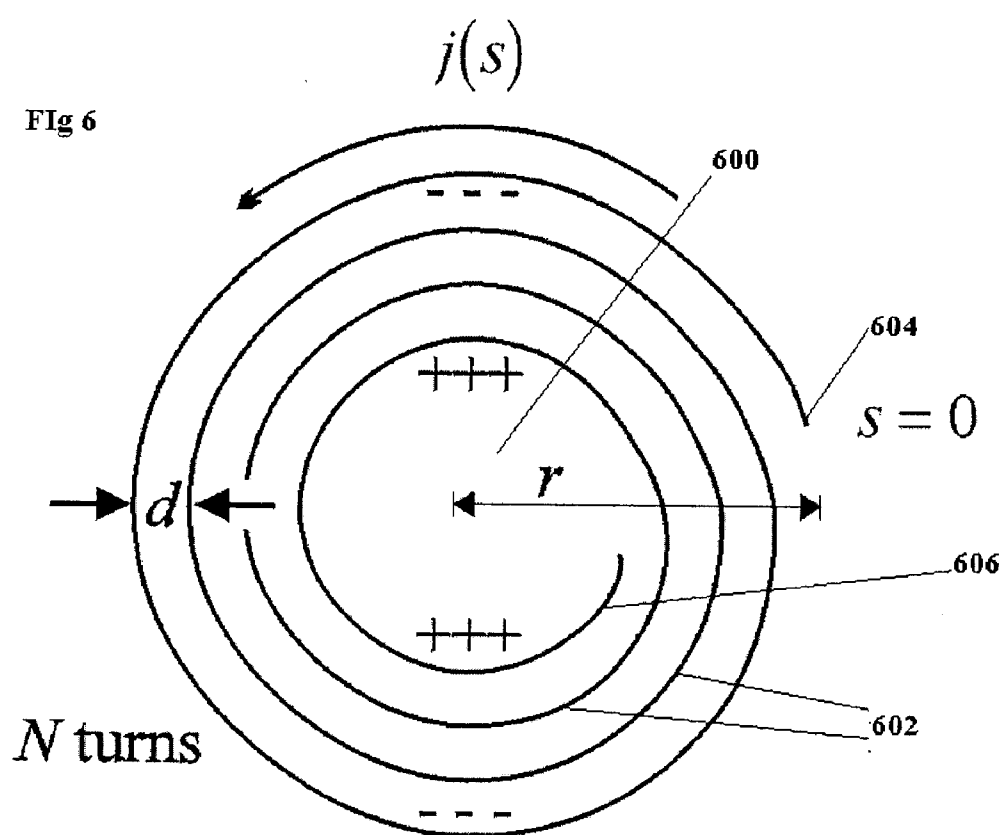
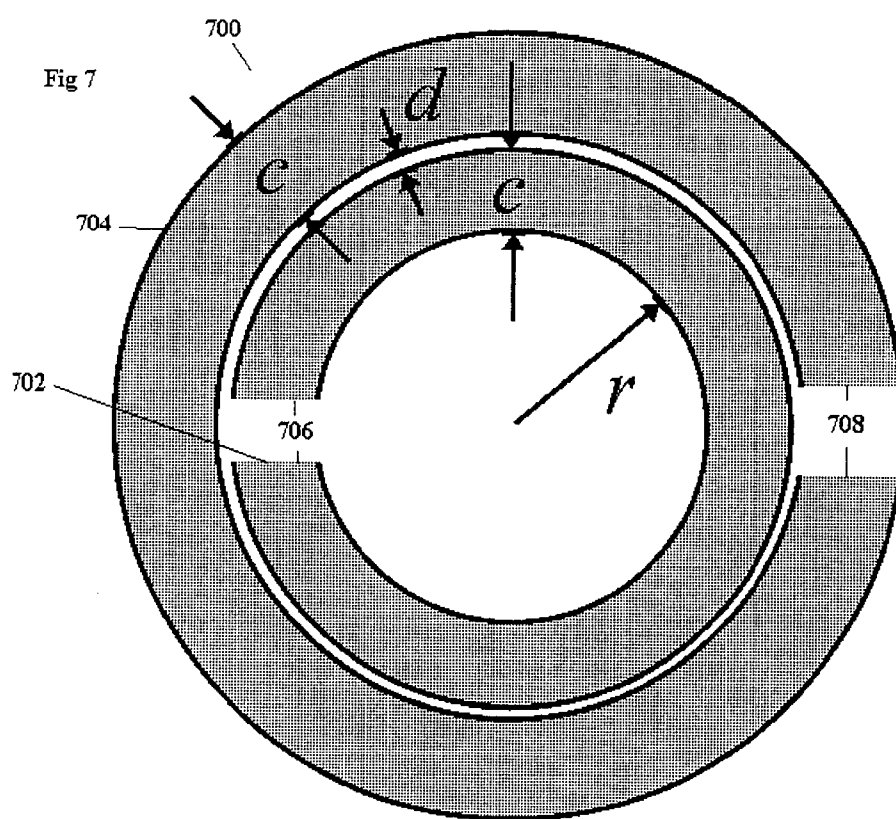


Fig 5







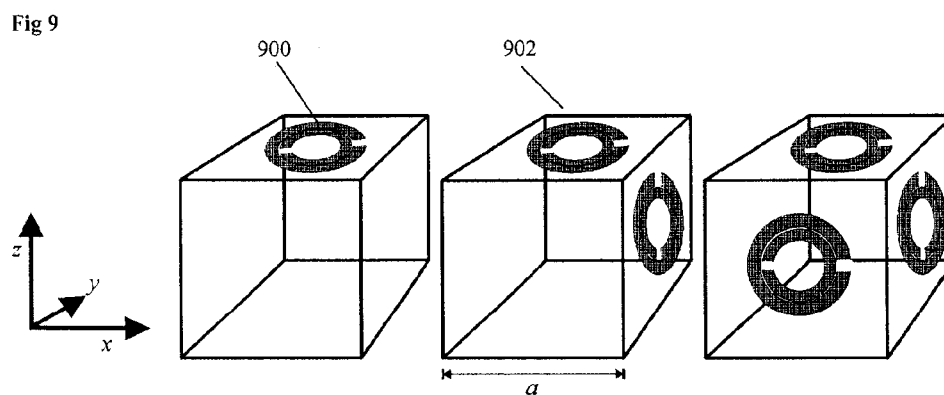
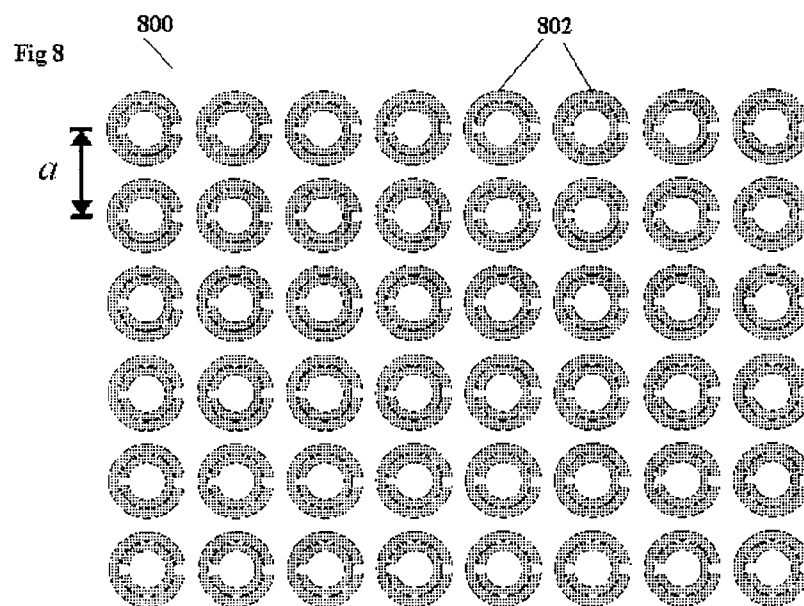


Fig 10

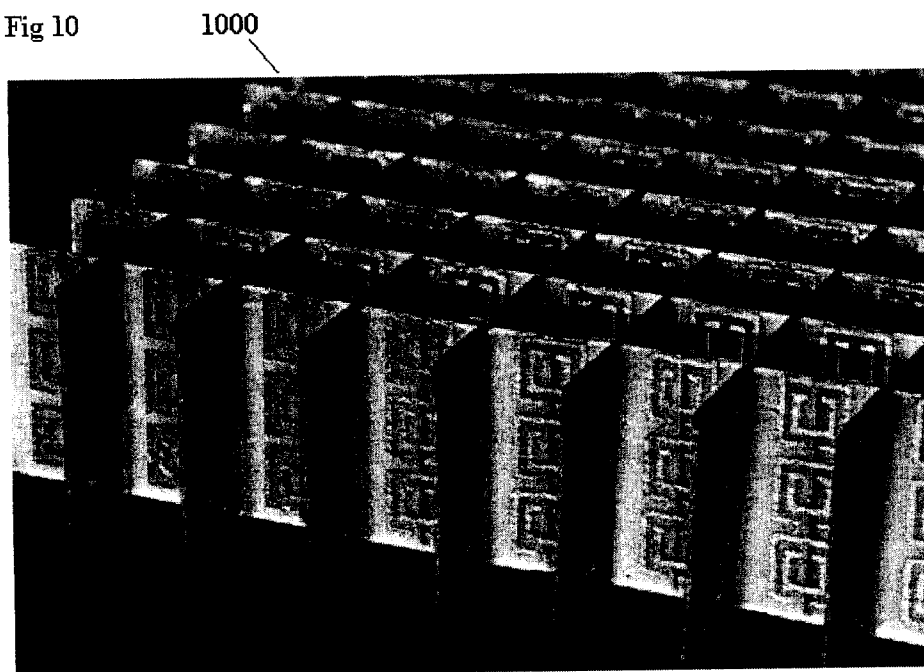


Fig 11

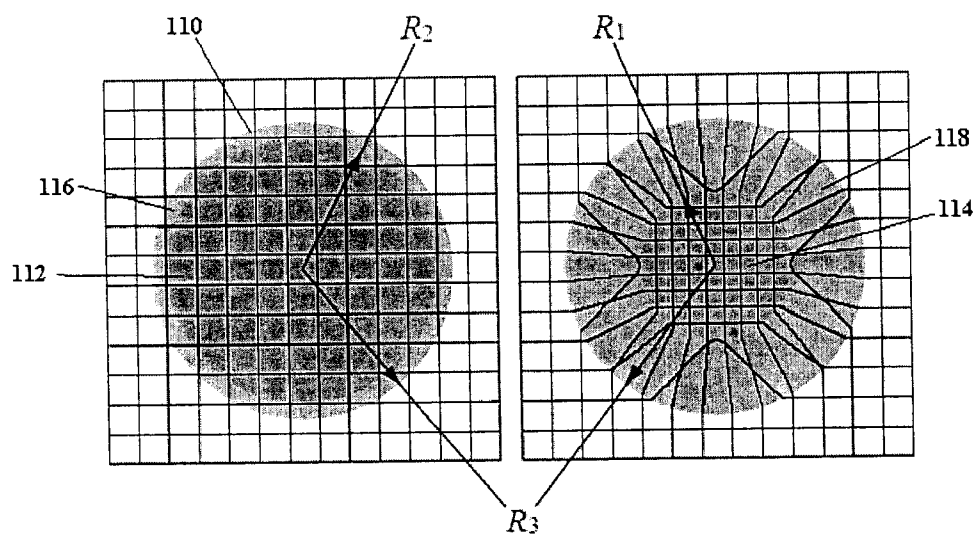
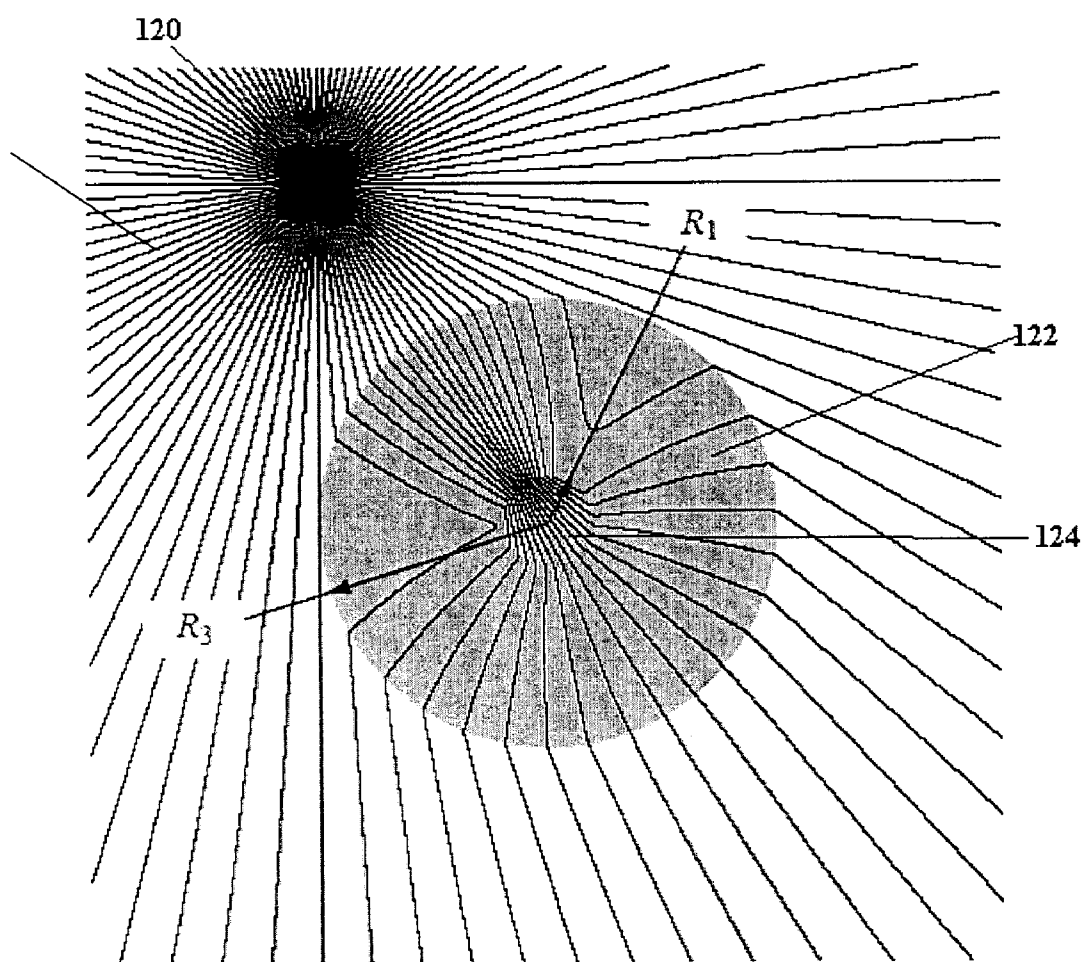




Fig 12



## ELECTROMAGNETIC CLOAKING METHOD

## BACKGROUND

**[0001]** In order to exploit electromagnetism, materials are commonly used to control and direct the electromagnetic fields. For example, a glass lens in a camera directs the rays of light to form an image, metal cages are used to screen sensitive equipment from electromagnetic radiation, and various forms of 'black bodies' are utilised to prevent unwanted reflections. One aspect of electromagnetism which is of particular interest, is the use of materials in the manipulation of electromagnetic waves such as to conceal or cloak objects or volumes of space from detection by an outside observer.

**[0002]** Several known methods exist which attempt to achieve electromagnetic concealment of objects. For example, it is possible to use a series of cameras to project an image to an observer of what he would see if an object in question were not blocking his view path. As a result, the observer does not realise that the object is present. This method, however, relies on the use of active components, and depends heavily on the relative positioning of the object, cameras and observer at all times.

**[0003]** Further known concealment methods include traditional "stealth technology" and the use of low radar cross section structures. These are designed to minimize back reflection of radar or other electromagnetic waves. Whilst these structures can provide a reduced or altered electromagnetic signature, because they involve either the scattering of incident waves away from the target or absorbing incident waves, the objects which they hide are still detectable in transmission.

**[0004]** In their paper, Physics Rev. E95, 016623 (2005), A Alu and N Engheta suggest a scheme for the concealment of spherical and cylindrical objects through the use of plasmonic and metamaterial 'cloaks' or covers. Whilst this paper provides a method of reducing the total scattering cross section of such objects, it relies on a specific knowledge of the shape and material properties of the object being hidden. In particular, the electromagnetic cloak and the concealed object form a composite, whose scattering properties can be reduced in the lowest order approximation. Therefore, if the shape of the object changes, the shape of the cloak must change accordingly. Furthermore, this method relies on a resonance effect, such that if the frequency drifts away from its resonant peak, the method is less effective. It is therefore a narrowband method, which cannot be implemented for broadband applications.

**[0005]** A further aspect of electromagnetism which is of interest is the use of materials in electromagnetic sensing and energy harvesting applications. Several known devices exist in this area, such as satellite dishes and solar energy panels. Whilst such prior art devices are operable to collect or detect electromagnetic radiation incident upon them from a number of different directions, and can be moveable to capture radiation incident from any desired direction, they do not have the capability to capture electromagnetic radiation incident from all directions at any given time. Problems therefore arise in applications when the direction of the electromagnetic source is initially unknown or constantly

changing, such as in solar energy collection and microwave energy beaming on mobile platforms.

## SUMMARY

**[0006]** The invention is set out in the claims. According to a first embodiment, because a method is provided in which those rays which would have passed through a particular volume of space are deflected around the volume and returned to their original trajectory, an observer would conclude that the rays had passed directly through that volume of space. This will be the case regardless of the relative positioning of the observer and the concealed volume. Furthermore, because no radiation can get into the concealed volume nor any radiation gets out, an object of any shape or material placed in the concealed volume will be invisible to the observer.

**[0007]** In one aspect, the invention utilises a co-ordinate transformation approach which is independent of the sizes of the concealed and concealing volume and does not suffer from any of the fundamental scaling issues which affect known concealment schemes. It is also possible to use the transformation method for any shape of concealed or concealing volume. The wavelength of the electromagnetic radiation does not appear in the solution, such that the invention can be applied for any size structure and for any wavelength, and for near and far fields.

**[0008]** In a further embodiment of the invention, all electromagnetic fields which are incident on an outer surface of a particular volume of space are concentrated into a inner core region, regardless of their direction of incidence on the outer surface. This enables a detector or collector to be placed at the inner core into which the electromagnetic fields have been concentrated, allowing it to interact with the intensified fields from all directions at that location. Because a method is described in which those rays which pass through the particular volume of space are returned to their original trajectory outwards of its outer surface, an observer would conclude that the rays had passed directly through that volume of space, regardless of the relative positioning of the observer and the volume in question. In addition, the present invention enables a detector placed within the inner core region to have its material properties matched to the surrounding layer such that it will also be invisible to an observer viewing the set up from any direction.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0009]** FIG. 1 is a cross-sectional ray trajectory diagram for a sphere of radius  $r < R_1$  cloaked within an annulus of radius  $R_1 < r < R_2$ , assuming that  $R_2 \gg \lambda$ ;

**[0010]** FIG. 2a shows a field line in free space plotted on a Cartesian mesh;

**[0011]** FIG. 2b shows the field line and background coordinates of FIG. 2a both distorted by the same transformation;

**[0012]** FIG. 3 is a cross-sectional view of the electrostatic displacement field lines for a sphere of radius  $r < R_1$  cloaked within an annulus of radius  $R_1 < r < R_2$ , located close to a point charge, assuming that  $R_2 \ll \lambda$ ;

**[0013]** FIG. 4a is a three-dimensional depiction of the diversion of electromagnetic rays around a cloaked volume, according to the present invention;

[0014] FIG. 4b is a three-dimensional depiction of the diversion of electromagnetic rays around a cloaked surface, according to the present invention;

[0015] FIG. 5 shows a front perspective view of a 'Swiss-roll' metamaterial;

[0016] FIG. 6 shows a top view of the 'Swiss-roll' metamaterial of FIG. 5;

[0017] FIG. 7 shows a single split ring metamaterial;

[0018] FIG. 8 shows a plan view of a split ring structure in a square array, lattice spacing  $a$ ;

[0019] FIG. 9 depicts the building of three-dimensional split ring resonator (SRR) at unit cell level;

[0020] FIG. 10 is a prior-art negative index metamaterial comprising SRR's and wires;

[0021] FIG. 11 is a cross-sectional ray trajectory diagram of a concentration device of radius  $R_3$  in which a spherical volume of space radius  $R_2$  is compressed to a smaller volume of space radius  $R_1$ ; and

[0022] FIG. 12 is a cross-sectional ray trajectory diagram in which rays from a point source incident on a sphere radius  $R_3$  are concentrated into an inner sphere radius  $R_1$ .

#### DETAILED DESCRIPTION

[0023] In overview, according to a first embodiment the invention provides a method of concealing an object or volume of space by means of redirecting the electromagnetic field lines around it. Any field lines which normally would flow through the concealed volume are redirected through a surrounding concealing volume. Outside of the cloaking structure, the field lines remain unperturbed. The cloaking structure is formed from a metamaterial, that is a material designed to exhibit the specific material parameters required for cloaking the object or volume in question. In particular, the electric permittivity  $\epsilon$  and magnetic permeability  $\mu$  and hence the refractive index  $n$  of the cloaking metamaterial can be varied effectively continuously spatially in order to manipulate the electromagnetic field lines and hence effectively conceal the enclosed volume. As a result of the invention, the concealed volume is undetectable to an outside observer, and any electromagnetic radiation produced by an object within the concealed volume cannot escape from it.

[0024] In a further embodiment the invention provides a method of concentrating the electromagnetic fields incident upon the outer surface of a concentrator device into an inner core region. The concentrator structure comprises a concentrating volume and a collecting volume. Any field lines which would normally flow through the concentrating volume are redirected into an inner collecting volume. Outside of the concentrator annulus surrounding the concentrating volume, the field lines remain unperturbed. The concentrator structure is formed from a metamaterial in a similar manner to that described above for the cloaking structure above.

[0025] Whilst, as is outlined in more detail below, the transformation method described herein can be applied to conceal any desired volume using any desired cloaking structure, for simplicity it will first be described in relation to the simple spherical case as shown in FIG. 1. According to FIG. 1, the volume to be hidden is a sphere **100** of radius  $R_1$  and the cloaking material is contained within the annulus **102** of radius  $R_1 < r < R_2$ . In order to create a secure, radiation-free volume within the sphere **100** of radius  $R_1$ , all those electromagnetic field lines **104** which normally would flow through the sphere **106** of radius  $r < R_2$  must therefore be

compressed into the cloaking annulus **102**  $R_1 < r < R_2$ . That is, in order to remove the sphere **100** of radius  $R_1$  from view, the volume within that sphere **100** plus the volume within the annulus **102** must all be mapped onto the annulus **102** of radius  $R_1 < r < R_2$ . In the medium outside of the sphere **106**  $r < R_2$ , the electromagnetic field lines **104** must remain unperturbed.

[0026] The theory of propagation of electromagnetic waves is well known and so only the relevant aspects are summarised here in the context of the invention. In free space, the magnetic field strength  $H$  is related to the magnetic field intensity  $B$  and the magnetic permeability of free space,  $\mu_0$ , via the equation  $B = \mu_0 H$ . The electric field  $E$  in free space is related to the electric displacement field  $D$  and electric permittivity of free space  $\epsilon_0$  via the equation  $D = \epsilon_0 E$ . In a dielectric the value of  $\epsilon$  and  $\mu$  are modified by the relative permittivity and permeability value  $\epsilon_r$ ,  $\mu_r$  and the refractive index of the invention is given by

$$n_r = \sqrt[3]{\epsilon \mu}.$$

As will be well known to the skilled person in the art, the three vectors  $E$ ,  $H$ , and  $S$  are mutually orthogonal, with the Poynting vector  $S$  being calculable via the vector cross product  $S = E \times H$ . The Poynting vector  $S$  gives the direction and magnitude of energy flow per unit area per unit time of an electromagnetic wave, and in a ray trajectory diagram such as that shown in FIG. 1, the direction of the rays of light correspond to the electromagnetic field lines and follow the direction of the Poynting vector. In order to implement this invention therefore, it is necessary to focus or redirect any of the electric displacement field  $D$ , the magnetic field intensity  $B$ , and the Poynting vector  $S$  so that they avoid the sphere **100** of radius  $R_1$ , and return undisturbed to their original trajectories.

[0027] As described in more detail below the approach further requires solution of Maxwell's equations in relation to the redirected fields. For ease of depiction, redirection of the Poynting vector in particular will be addressed in the following description.

[0028] In order to calculate the electromagnetic properties which a cloaking structure must possess in order to effectively implement the desired cloaking effects, the first step is to calculate the distortion which must be applied to the Poynting vector  $S$  so that the rays do not pass through the sphere **100** of radius  $R_1$ . As shown in FIGS. 2a and 2b, this is achieved by recording the initial configuration of each ray, which would occur in the absence of a cloaked volume and cloaking material, on a known geometric mesh, such as a spherical or Cartesian mesh. For example in FIG. 2a, a single ray **200** is plotted on a Cartesian mesh **202**: Once the appropriate rays **200** have been plotted on it, the Cartesian mesh **202** is stretched or distorted in such a manner that the rays plotted thereon become distorted to follow their new desired path, avoiding the cloaked volume. The distortions which are imposed on the Cartesian mesh **202** in order to achieve this can then be recorded as a coordinate transformation between the original Cartesian mesh **202** and a second transformed mesh **204**, wherein the second mesh is defined by:

$$q_1(x,y,z), q_2(x,y,z), q_3(x,y,z) \quad (1)$$

[0029] In this second mesh **204**, lines of constant  $q_2, q_3$  define the generalized  $q_1$  axis, and so on. It will be seen that conversely if the second mesh **204** comprised a set of points defined by equal increments along the  $q_1, q_2, q_3$  axes, it would appear distorted in the  $x, y, z$  Cartesian frame, as a comparison of FIGS. **2a** and **2b** clearly demonstrates.

[0030] The benefit of performing this transformation is that, as described below, it can be shown that it is possible to solve Maxwell's equations in the same form in the transformed geometry as in the original geometry, with only a corresponding transform of the spatially distributed values of  $\epsilon$  and  $\mu$  being required. This can be understood intuitively from the recognition that variation of the permittivity  $\epsilon$  and permeability  $\mu$  values, and hence the refractive index  $n$  in a space, is equivalent to distorting the geometry of the space as seen by a light ray. It will be noted that the approach specifically addresses modification of the value of  $\epsilon$  and  $\mu$  individually rather than of the refractive index  $n=\pm\sqrt{\epsilon\mu}$ . In particular this allows reflection between interfaces of different media to be removed by ensuring impedance ( $Z$ ) matching where

$$Z = \sqrt{\frac{\mu}{\epsilon}}.$$

[0031] As will be known to the skilled person, Maxwell's equations in a system of Cartesian coordinates take the form:

$$\begin{aligned}\nabla \times \mathbf{E} &= -\mu \mu_0 \partial \mathbf{H} / \partial t \\ \nabla \times \mathbf{H} &= +\epsilon \epsilon_0 \partial \mathbf{E} / \partial t\end{aligned}\quad (2)$$

where both electric permittivity  $\epsilon$  and magnetic permeability  $\mu$  depend on position. As described in Annex 1, when a coordinate transformation is applied to these equations, in the new co-ordinate system they take the form:

$$\begin{aligned}\nabla_q \times \hat{\mathbf{E}} &= -\mu_q \hat{\mathbf{a}} \partial \hat{\mathbf{H}} / \partial t, \\ \nabla_q \times \hat{\mathbf{H}} &= +\epsilon_q \hat{\mathbf{a}} \partial \hat{\mathbf{E}} / \partial t\end{aligned}\quad (3)$$

where  $\epsilon$  and  $\mu$  are in general tensors, and  $\hat{\mathbf{E}}, \hat{\mathbf{H}}$  are renormalized electric and magnetic fields. All four quantities are simply related to originals. In other words the form of Maxwell's equation is preserved by a co-ordinate transformation: the co-ordinate transformation does not change the fact that we are still solving Maxwell's equations, it simply changes the definition of  $\epsilon, \mu$ .

[0032] In particular, as is shown in detail in Annex 1, the effect of the transformation on  $\mu$  and  $\epsilon$  is to scale them both by a common factor. A generalized solution to this is shown in Annex 1, however in the case of an orthogonal geometry (Cartesian, spherical or cylindrical) but the renormalized values of the permittivity and permeability are:

$$\epsilon'_u = \epsilon_u \frac{Q_u Q_v Q_w}{Q_u^2}, \quad (4)$$

$$\mu'_u = \mu_u \frac{Q_u Q_v Q_w}{Q_u^2}, \text{ etc.}$$

$$\begin{aligned}E'_u &= Q_u E_u, H'_u = Q_u H_u, \text{ etc.} \\ \text{where,}\end{aligned}\quad (5)$$

-continued

$$Q_u^2 = \left( \frac{\partial x}{\partial u} \right)^2 + \left( \frac{\partial y}{\partial u} \right)^2 + \left( \frac{\partial z}{\partial u} \right)^2 \quad (6)$$

$$Q_v^2 = \left( \frac{\partial x}{\partial v} \right)^2 + \left( \frac{\partial y}{\partial v} \right)^2 + \left( \frac{\partial z}{\partial v} \right)^2$$

$$Q_w^2 = \left( \frac{\partial x}{\partial w} \right)^2 + \left( \frac{\partial y}{\partial w} \right)^2 + \left( \frac{\partial z}{\partial w} \right)^2$$

And:

$$B' \mu_0 \mu' H' \text{ and } D' = \epsilon_0 \epsilon E' \quad (7)$$

[0033] Referring back to the spherical case as shown in FIG. **1**, the natural choice of mesh on which to plot the original ray configuration is a spherical one, which uses the co-ordinates  $r, \theta$  and  $\phi$ . The co-ordinate transformation operates by taking all the fields in the sphere **106** of radius  $r < R_2$  and compressing them into the annulus **102** of radius  $R_1 < r < R_2$ . This is achieved by any transformation of the form:

$$r' = R_1 + \frac{f(r) - f(0)}{f(R_2) - f(0)} (R_2 - R_1), \quad (8)$$

$$\theta' = \theta,$$

$$\phi' = \phi$$

where  $f(r)$  is a monotonically increasing function of  $r$ , this will map the entire interior of a sphere **106** of radius  $R_2$  into an annulus bounded by two spheres **100, 106** radii  $R_1$  and  $R_2$  respectively. There is symmetry for  $\phi$  and  $\theta$  because the field lines are being compressed radially only, so their angular positioning is not distorted.

[0034] The simplest solution to equation (8) arises when  $f(r)=r$ , which simplifies to give:

$$r' = R_1 + r(R_2 - R_1)/R_2,$$

$$\theta' = \theta,$$

$$\phi' = \phi \quad (9)$$

[0035] In order to ascertain the electromagnetic properties which will be required of the cloaking annulus **102** material so that it achieves the desired result of cloaking any object in the sphere **100**  $R_1$  the transformation which has been imposed on  $r, \phi$  and  $\theta$  must be applied in an analogous manner to  $\epsilon$  and  $\mu$ , as shown for the general case in Annex 1. At each point  $(x, y, z)$  in space,  $\epsilon$  and  $\mu$  will have component  $(\epsilon_x, \epsilon_y, \epsilon_z), (\mu_x, \mu_y, \mu_z)$  which must be transformed to spherical coordinate value  $(\epsilon'_r, \epsilon'_\theta, \epsilon'_\phi), (\mu'_r, \mu'_\theta, \mu'_\phi)$  in the transformed geometry.

[0036] We do this in two steps:

First transform to spherical coordinates without any compression,

[0037]

$$x=r \cos\phi \sin\theta, y=r \sin\phi \sin\theta, Z=r \cos\theta \quad (A1)$$

so that, as shown in equation (4) above, in the new frame,

$$\begin{aligned}\tilde{\varepsilon}_i &= \varepsilon_i \frac{Q_1 Q_2 Q_3}{Q_i^2}, \\ \tilde{\mu}_i &= \mu_i \frac{Q_1 Q_2 Q_3}{Q_i^2}\end{aligned}\quad (\text{A2})$$

We calculate,

[0038]

$$\begin{aligned}Q_r^2 &= \left(\frac{\partial x}{\partial r} = \cos\phi \sin\theta\right)^2 + \left(\frac{\partial y}{\partial r} = \sin\phi \sin\theta\right)^2 + \left(\frac{\partial z}{\partial r} = \cos\theta\right)^2 = 1 \\ Q_\theta^2 &= \left(\frac{\partial x}{\partial \theta} = r \cos\phi \cos\theta\right)^2 + \left(\frac{\partial y}{\partial \theta} = r \sin\phi \cos\theta\right)^2 + \left(\frac{\partial z}{\partial \theta} = -r \sin\theta\right)^2 = r^2 \\ Q_\phi^2 &= \left(\frac{\partial x}{\partial \phi} = -r \sin\phi \sin\theta\right)^2 + \left(\frac{\partial y}{\partial \phi} = +r \cos\phi \sin\theta\right)^2 + \left(\frac{\partial z}{\partial \phi} = 0\right)^2 = r^2 \sin^2\theta\end{aligned}\quad (\text{A3})$$

and hence,

$$\begin{aligned}\tilde{\varepsilon}_r &= \tilde{\mu}_r \\ &= \frac{Q_r Q_\theta Q_\phi}{Q_r^2} \varepsilon_r \\ &= \frac{r^2 \sin\theta}{1} \varepsilon_r \\ &= r^2 \sin\theta \varepsilon_r \\ \tilde{\varepsilon}_\theta &= \tilde{\mu}_\theta \\ &= \frac{Q_r Q_\theta Q_\phi}{Q_\theta^2} \varepsilon_\theta \\ &= \frac{r^2 \sin\theta}{r^2} \varepsilon_\theta \\ &= \sin\theta \varepsilon_\theta \\ \tilde{\varepsilon}_\phi &= \tilde{\mu}_\phi \\ &= \frac{Q_r Q_\theta Q_\phi}{Q_\phi^2} \varepsilon_\phi \\ &= \frac{r^2 \sin\theta}{r^2 \sin^2\theta} \varepsilon_\phi \\ &= \frac{1}{\sin\theta} \varepsilon_\phi\end{aligned}\quad (\text{A4})$$

where  $\varepsilon_r$ ,  $\varepsilon_\theta$ ,  $\varepsilon_\phi$ , the three components of the permittivity tensor in the original Cartesian frame, and we assume that the permittivity and permeability are equal. Note that we can easily extract the Cartesian view of  $\varepsilon_r$ ,  $\varepsilon_\theta$ ,  $\varepsilon_\phi$  from (A4) by removing the appropriate factors of r.

[0039] In order to create a protected space inside the sphere radius  $R_1$  we make a further transformation to a new cylindrical system in which the radius is compressed taking any ray trajectories with it. It is noted that computer programs work in Cartesian coordinates and therefore that it is possible to re-express the compressed radial coordinate system in terms of a compressed Cartesian system,  $x' y' z'$ , by removing factors of  $r'$ .

Consider the transformation from equation (9),

[0040]

$$r' = R_1 + r(R_2 - R_1)/R_2, \theta' = \theta, \phi' = \phi \quad (\text{A5})$$

which can be re-expressed as,

$$r = \frac{(r' - R_1)R_2}{R_2 - R_1}, \theta' = \theta, \phi' = \phi \quad (\text{A6})$$

We calculate,

[0041]

$$\begin{aligned}Q_{r'}^2 &= \left(\frac{\partial r}{\partial r'} = \frac{R_2}{R_2 - R_1}\right)^2 + \left(\frac{\partial \theta}{\partial r'} = 0\right)^2 + \left(\frac{\partial \phi}{\partial r'} = 0\right)^2 = \left[\frac{R_2}{R_2 - R_1}\right]^2 \\ Q_{\theta'}^2 &= \left(\frac{\partial r}{\partial \theta'} = 0\right)^2 + \left(\frac{\partial \theta}{\partial \theta'} = 1\right)^2 + \left(\frac{\partial \phi}{\partial \theta'} = 0\right)^2 = 1 \\ Q_{\phi'}^2 &= \left(\frac{\partial r}{\partial \phi'} = 0\right)^2 + \left(\frac{\partial \theta}{\partial \phi'} = 0\right)^2 + \left(\frac{\partial \phi}{\partial \phi'} = 1\right)^2 = 1\end{aligned}\quad (\text{A7})$$

so that in the new frame,

for  $R_1 < r' < R_2$

$$\begin{aligned}\tilde{\varepsilon}_{r'} &= \tilde{\mu}_{r'} \\ &= \tilde{\varepsilon}_r \frac{Q_{r'} Q_{\theta'} Q_{\phi'}}{Q_{r'}^2} \\ &= \frac{(R_2 - R_1)}{R_2} r^2 \sin\theta \varepsilon_r \\ &= \frac{(R_2 - R_1)}{R_2} \left[\frac{(r' - R_1)R_2}{R_2 - R_1}\right]^2 \sin\theta \varepsilon_r \\ &= \frac{R_2 (r' - R_1)^2}{R_2 - R_1} \sin\theta \varepsilon_r\end{aligned}\quad (\text{A8a})$$

$$\begin{aligned}\tilde{\varepsilon}_{\theta'} &= \tilde{\mu}_{\theta'} \\ &= \tilde{\varepsilon}_\theta \frac{Q_{r'} Q_{\theta'} Q_{\phi'}}{Q_{\theta'}^2} \\ &= \frac{R_2}{R_2 - R_1} \sin\theta \varepsilon_\theta\end{aligned}$$

$$\begin{aligned}\tilde{\varepsilon}_{\phi'} &= \tilde{\mu}_{\phi'} \\ &= \tilde{\varepsilon}_\phi \frac{Q_{r'} Q_{\theta'} Q_{\phi'}}{Q_{\phi'}^2} \\ &= \frac{R_2}{R_2 - R_1} \frac{1}{\sin\theta} \varepsilon_\phi\end{aligned}$$

[0042] Alternatively we can reinterpret these values in a Cartesian coordinate frame,  $x'y'z'$ , which is easily done by comparison with (A4),

$$\begin{aligned}\varepsilon_{r'} &= \mu_{r'} \\ &= \frac{R_2}{R_2 - R_1} \frac{(r' - R_1)^2}{r'^2} \varepsilon_r\end{aligned}\quad (\text{10})$$

-continued

$$\begin{aligned}\epsilon_{\theta'} &= \mu_{\theta'} \\ &= \frac{R_2}{R_2 - R_1} \epsilon_{\theta} \\ \tilde{\epsilon}_{\theta'} &= \tilde{\mu}_{\theta'} \\ &= \frac{R_2}{R_2 - R_1} \epsilon_{\theta}\end{aligned}$$

where we have assumed that the starting material is vacuum.  
for  $R_2 < r'$

$$\begin{aligned}\tilde{\epsilon}_{r'} &= \tilde{\mu}_{r'} = r'^2 \sin\theta' \epsilon_{r'} \\ \tilde{\epsilon}_{\theta'} &= \tilde{\mu}_{\theta'} = \sin\theta' \epsilon_{\theta'} \\ \tilde{\epsilon}_{\varphi'} &= \tilde{\mu}_{\varphi'} = \frac{1}{\sin\theta'} \epsilon_{\varphi'}\end{aligned}\quad (A7b)$$

$$\text{In free space, } \epsilon_r' = \mu_r' = \epsilon_{\theta}' = \mu_{\theta}' = \epsilon_{\varphi}' = \mu_{\varphi}' = 1 \quad (11)$$

for  $r' < R_1$  we may choose any value we please for the dielectric functions since radiation never penetrates into this region. In this region  $\epsilon'$ ,  $\mu'$  are free to take any value without restriction whilst still remaining invisible, and not contributing to electromagnetic scattering. This will be the case for all cloaked volumes, regardless of their shape or size.

**[0043]** If a suitable cloaking material can be implemented for the annulus **102** of radius  $R_1 < r < R_2$ , this will exclude all fields from entering the central region **100** of radius  $R_1$  and, conversely, will prevent all fields from escaping from this region. The cloaking structure itself and any object placed in the concealed sphere **100**  $R_1$  will therefore be undetectable in either reflection or transmission. It will be noted that at all points in the medium the impedance

$$z = \sqrt{\frac{\mu}{\epsilon}} = 1$$

such that no unwanted reflection in the medium, caused by impedance mismatch, takes place.

**[0044]** It is noted that if the impedance  $z = \sqrt{\mu/\epsilon} = 1$  is achieved at all points in the metamaterial, the cloaking structure and concealed volume will appear to contain only free space, and so will be invisible if embedded in free space. If the cloaking structure is embedded in another medium the effect will differ, for example if embedded in water it would have the appearance of a bubble. In order to make the cloaking structure invisible in another medium it is necessary to match the ratio of  $\mu$  and  $\epsilon$  in the metamaterial to that of the surrounding medium at the interface between the two. As the skilled person will appreciate, whilst this changes the numerical values of  $\epsilon$  and  $\mu$  in the cloaking structure metamaterial, the general transformation theory outlined in Annex 1 remains the same. That is, because the present invention enables  $\epsilon$  and  $\mu$  to be controlled in a metamaterial independently of one another, it is possible to achieve any desired value of  $z$ , to match the impedance of the metamaterial to that of its surroundings.

**[0045]** Whilst in FIG. 1 the cloaking annulus **102** is depicted as being relatively thick, this does not have to be the case. The solution is not dependent on shell thickness or any other length scales, such that it does not suffer from any scaling issues. Additionally, the solution provided holds in both in the near and far fields, because the solution does not depend on the wavelength  $\lambda$ . This is demonstrated in FIGS. 1 and 3. For purposes of illustration, suppose that  $R_2 \gg \lambda$  where  $\lambda$  is the wavelength so that we can use the ray approximation to plot the Poynting vector. If our system is then exposed to a source of radiation at infinity we can perform the ray tracing exercise shown in FIG. 1. Rays **104** in this figure result from numerical integration of a set of Hamilton's equations obtained by taking the geometric limit of Maxwell's equations with anisotropic, inhomogeneous media. This integration provides an independent confirmation that the configuration specified by (9) and (10) excludes rays from the interior region **100**. Alternatively if  $R_2 < \lambda$  and we locate a point charge **306** nearby, the electrostatic (or magnetostatic) approximation applies. A plot of the local electrostatic displacement field which results is shown in FIG. 3.

**[0046]** The theoretical solution outlined above can be demonstrated using a ray-tracing program to calculate the ray trajectories. According to such a program, a specified material is assumed to exist around a central volume that is to be 'cloaked', or rendered invisible to the user. Using the specified parameters as input, the ray-tracing code confirms the theoretical prediction. Ray tracing programs of this type will be well known to those skilled in the art, although some existing programs will not be able to deal with the complexity of the problem for this invention. In FIGS. 4a and 4b, a ray tracing program has been used which was developed from a custom ray tracing code based on a Hamiltonian formulation to solve Maxwell's equations in the geometric limit (ie zero wavelength limit). The results are shown for a spherical structure **400** and a cylindrical structure **402** respectively, wherein the transformed parameters  $\epsilon$  and  $\mu$  in the cylindrical case are calculated in a similar manner to those for the sphere, as shown below:

**[0047]** First transform to cylindrical coordinates without any compression,

$$x = r \cos\theta, \quad y = r \sin\theta, \quad Z = z \quad (A8)$$

so that in the new frame,

$$\tilde{\epsilon}_i = \epsilon_i \frac{Q_1 Q_2 Q_3}{Q_i^2}, \quad \tilde{\mu}_i = \mu_i \frac{Q_1 Q_2 Q_3}{Q_i^2} \quad (A9)$$

We calculate,

**[0048]**

$$\begin{aligned}Q_r^2 &= \left(\frac{\partial x}{\partial r} = \cos\theta\right)^2 + \left(\frac{\partial y}{\partial r} = \sin\theta\right)^2 + \left(\frac{\partial z}{\partial r} = 0\right)^2 = 1 \\ Q_{\theta}^2 &= \left(\frac{\partial x}{\partial \theta} = -r \sin\theta\right)^2 + \left(\frac{\partial y}{\partial \theta} = +r \cos\theta\right)^2 + \left(\frac{\partial z}{\partial \theta} = 0\right)^2 = r^2 \\ Q_z^2 &= \left(\frac{\partial x}{\partial z} = 0\right)^2 + \left(\frac{\partial y}{\partial z} = 0\right)^2 + \left(\frac{\partial z}{\partial z} = 1\right)^2 = 1\end{aligned}\quad (A10)$$

and hence,

$$\begin{aligned}\tilde{\epsilon}_r &= \tilde{\mu}_r = \frac{Q_r Q_\theta Q_Z}{Q_r^2} \epsilon_r = r \epsilon_r \\ \tilde{\epsilon}_\theta &= \tilde{\mu}_\theta = \frac{Q_r Q_\theta Q_Z}{Q_\theta^2} \epsilon_\theta = r^{-1} \epsilon_\theta \\ \tilde{\epsilon}_Z &= \tilde{\mu}_Z = \frac{Q_r Q_\theta Q_Z}{Q_Z^2} \epsilon_Z = r \epsilon_Z\end{aligned}\quad (\text{A11})$$

where  $\epsilon_r, \epsilon_\theta, \epsilon_Z$  the three components of the permittivity tensor in the original Cartesian frame, and we assume that the permittivity and permeability are equal. Note that we can easily extract the Cartesian view of  $\epsilon_r, \epsilon_\theta, \epsilon_Z$  from (A13) by removing the appropriate factors of  $r$ .

**[0049]** In order to create a protected space inside a cylinder radius  $R_1$ , we make a further transformation to a new cylindrical system in which the radius is compressed taking any ray trajectories with it. It is noted that computer programs work in Cartesian coordinates and therefore that it is possible to re-express the compressed radial coordinate system in terms of a compressed Cartesian system,  $x'y'z'$ , by removing factors of  $r'$ .

Consider the transformation,

$$\begin{aligned}r' &= R_1 + r(R_2 - R_1) / R_2, \theta' = \theta, Z' = Z \\ \text{or,}\end{aligned}\quad (\text{A12})$$

$$r = \frac{(r' - R_1)R_2}{R_2 - R_1}, \theta' = \theta, Z' = Z \quad (\text{A13})$$

We calculate,

$$\begin{aligned}Q_{r'}^2 &= \left( \frac{\partial r}{\partial r'} = \frac{R_2}{R_2 - R_1} \right)^2 + \left( \frac{\partial \theta}{\partial r'} = 0 \right)^2 + \\ &\quad \left( \frac{\partial Z}{\partial r'} = 0 \right)^2 + \left[ \frac{R_2}{R_2 - R_1} \right]^2 \\ Q_{\theta'}^2 &= \left( \frac{\partial r}{\partial \theta'} = 0 \right)^2 + \left( \frac{\partial \theta}{\partial \theta'} = 1 \right)^2 + \left( \frac{\partial Z}{\partial \theta'} = 0 \right)^2 = 1 \\ Q_{Z'}^2 &= \left( \frac{\partial r}{\partial Z'} = 0 \right)^2 + \left( \frac{\partial \theta}{\partial Z'} = 0 \right)^2 + \left( \frac{\partial Z}{\partial Z'} = 1 \right)^2 = 1\end{aligned}\quad (\text{A14})$$

so that in the new frame,

for  $R_1 < r' < R_2$

$$\begin{aligned}\tilde{\epsilon}_{r'} &= \tilde{\mu}_{r'} \\ &= \tilde{\epsilon}_r \frac{Q_{r'} Q_{\theta'} Q_{Z'}}{Q_{r'}^2} \\ &= \frac{(R_2 - R_1)}{R_2} r \epsilon_r \\ &= \frac{(R_2 - R_1)}{R_2} \frac{(r' - R_1)R_2}{R_2 - R_1} \epsilon_r \\ &= (r' - R_1) \epsilon_r\end{aligned}\quad (\text{A15a})$$

-continued

$$\begin{aligned}\tilde{\epsilon}_{\theta'} &= \tilde{\mu}_{\theta'} \\ &= \tilde{\epsilon}_\theta \frac{Q_{r'} Q_{\theta'} Q_{Z'}}{Q_{\theta'}^2} \\ &= \frac{R_2}{R_2 - R_1} r^{-1} \epsilon_\theta \\ &= \frac{R_2}{R_2 - R_1} \frac{R_2 - R_1}{(r' - R_1)R_2} \epsilon_\theta \\ &= \frac{1}{(r' - R_1)} \epsilon_\theta\end{aligned}$$

$$\begin{aligned}\tilde{\epsilon}_{Z'} &= \tilde{\mu}_{Z'} \\ &= \tilde{\epsilon}_Z \frac{Q_{r'} Q_{\theta'} Q_{Z'}}{Q_{Z'}^2} \\ &= \frac{R_2}{R_2 - R_1} r \epsilon_Z \\ &= \frac{R_2}{R_2 - R_1} \frac{(r' - R_1)R_2}{R_2 - R_1} \epsilon_Z \\ &= \left[ \frac{R_2}{R_2 - R_1} \right]^2 (r' - R_1) \epsilon_Z\end{aligned}$$

for  $R_2 < r'$

$$\begin{aligned}\tilde{\epsilon}_{r'} &= \tilde{\mu}_{r'} = r' \epsilon_{r'} \\ \tilde{\epsilon}_{\theta'} &= \tilde{\mu}_{\theta'} = r'^{-1} \epsilon_{\theta'} \\ \tilde{\epsilon}_{Z'} &= \tilde{\mu}_{Z'} = r' \epsilon_{Z'}\end{aligned}\quad (\text{A15b})$$

for  $r' < R_1$  we may choose any value we please for the dielectric functions since radiation never penetrates into this region.

Alternatively we can reinterpret these values in a Cartesian coordinate frame,  $x'y'z'$ , which is easily done by comparison with (A4),

**[0052]**

$$\begin{aligned}\epsilon_{r'} &= \mu_{r'} \\ &= \frac{r' - R_1}{r'} \\ \epsilon_{\theta'} &= \mu_{\theta'} \\ &= \frac{r'}{(r' - R_1)} \\ \epsilon_{Z'} &= \mu_{Z'} \\ &= \left[ \frac{R_2}{R_2 - R_1} \right]^2 \frac{r' - R_1}{r'}\end{aligned}\quad (\text{A16})$$

where we have assumed that the starting material is vacuum.

**[0053]** FIGS. 4a and 4b show that the incident rays 404, 406 are diverted around a central region 400, 402 and emerge from the cloaking region 408, 410 apparently unperturbed, as predicted by the theoretical solution.

**[0054]** Whilst the theoretical solution has been confirmed by ray-tracing methods, in order to put the invention into effect a suitable material to form the cloaking structure has been developed.

**[0055]** The material parameters of the cloaking structure require that the components of  $\epsilon'$  equal those of  $\mu'$ , that  $\epsilon'$  and  $\mu'$  vary throughout space, and that the tensor components of  $\epsilon'$  and  $\mu'$  vary independently. The anticipated material is thus inhomogeneous and anisotropic. Moreover, the material parameters  $\epsilon'$  and  $\mu'$  must assume values less than unity and approach zero at the interface between the concealed region and the cloaking shell. Furthermore, it is noted that equation (6) is singular at  $r=R_1$ . This is unavoidable as can be seen by considering a ray headed directly towards the centre of the sphere **100** (FIG. 1). This ray does not know whether to be deviated up or down, left or right. Neighbouring rays **104** are bent around tighter and tighter arcs closer to the critical ray they are. This in turn implies very steep gradients in  $\epsilon'$  and  $\mu'$ . Parameters  $\epsilon'$  and  $\mu'$  are necessarily anisotropic in the cloaking material because space has been compressed anisotropically. This set of constraints is not attainable by conventional materials for example because finding matching values for  $\epsilon$  and  $\mu$  in the same waveband does not occur. However, given the rapid progress that has occurred over the past several years in artificial materials, a metamaterial can be practically designed that satisfies the specifications.

**[0056]** Metamaterials are artificially constructed 'materials' which can exhibit electromagnetic characteristics that are difficult or impossible to achieve with conventional materials. From an electromagnetic point of view, the wavelength,  $\lambda$ , of a wave passing through a material determines whether a collection of atoms or other objects can be considered a material and properties at the atomic level determine  $\epsilon$  and  $\mu$ . However, the electromagnetic parameters  $\epsilon$  and  $\mu$  need not arise strictly from the response of atoms or molecules: Any collection of objects whose size and spacing are much smaller than  $\lambda$  can be described by an  $\epsilon$  and  $\mu$ . In that case, the values of  $\epsilon$  and  $\mu$  are determined by the scattering properties of the structured objects. Although such an inhomogeneous collection may not satisfy an intuitive definition of a material, an electromagnetic wave passing through the structure cannot tell the difference, and, from the electromagnetic point of view, we have created an artificial material, or metamaterial. This properties of metamaterials are explained further in "Metamaterials and Refractive Index", D R Smith, J B Pendry, MCK. Wiltshire, VOL 305, SCIENCE 061081 (2004). which is incorporated herein by reference.

**[0057]** One useful property exhibited by certain metamaterials is that of artificial magnetism. It has been found that structures consisting of non-magnetic arrays of wire loops in which an external field can induce a current consequently produce an effective magnetic response. One such design is the so-called 'Swiss-roll' structure, as shown in FIG. 5. The roll **500** is manufactured by rolling an insulated metallic sheet around a cylinder **504**. A design with about 11 turns on a 1-cm-diameter cylinder gives a resonant response at 21 MHz. The metamaterial is formed by stacking together many of these cylinders. In this structure, the coiled copper sheets have a self-capacitance and self-inductance that create a resonance. The currents that flow when this resonance is activated couple strongly to an applied magnetic field, yielding an effective permeability that can reach quite high values. No current can flow around the coil except by self capacitance. As is shown in FIG. 6, when a magnetic field parallel to the cylinder **600** is switched on it induces currents (j) in the coiled sheets **602**, which are spaced a distance d apart from one another. Capacitance between the first **604**

and last **606** turns of the coil enables current to flow. This is described further in "Magnetism from Conductors and Enhanced Non-Linear Phenomena", J B Pendry, A J Holden, D J Robbins and W J Stewart IEEE Trans. Micr. Theory and Techniques, 47, 2075 (1999), which is incorporated herein by reference.

**[0058]** One problem with the Swiss-roll structures is that the continuous electrical path provided by metal cylinders can cause the metamaterial to respond like an effective metal when the electric field applied is not parallel to the cylinders, hence restricting its usefulness in certain applications. An adaptation described in the same paper which avoids this undesirable effect is the split ring resonator (SRR). The SRR is built up from a series of split rings, as shown in FIG. 7. Each split ring **700** comprises at least two concentric thin metal rings **702**, **704** of width c, spaced apart by a distance d, each one with a gap, **706**, **708**. By eliminating the continuous conducting path which the cylinders provide, an SRR eliminates most of the electrical activity along this direction.

**[0059]** As shown in FIG. 8, it is possible to form a planar split ring structure **800** from a series of split rings **802**, spaced a distance a apart. The two dimensional square array **800** shown in FIG. 8 can be made by printing with metallic inks. If each printed sheet is then fixed to a solid block of inert material, thickness a, the blocks can be stacked to give columns of rings. This would establish magnetic activity along the direction of stacking, z-axis.

**[0060]** The unit cell **900** of the stacked SRR structure is shown in FIG. 9 on the left. It is possible to form a symmetrical three dimensional structure starting from such a structure comprising successive layers of rings stacked along the z-axis. This is achievable by cutting up the structure into a series of slabs thickness a, making incisions in the y-z plane and being careful to avoid slicing through any of the rings. Each of the new slabs contains a layer of rings but now each ring is perpendicular to the plane of the slab and is embedded within. The next stage is to print onto the surface of each slab another layer of rings and stack the slabs back together again. The unit cell **902** of this second structure is shown in the middle of FIG. 9. In the final step, a third set of slabs is produced by cutting in the x-z plane, printing on the surface of the slabs, and reassembling. This results in a structure with cubic symmetry whose unit cell **904** is shown on the right of FIG. 9.

**[0061]** Similarly  $\epsilon$  can be governed by an array of thin wires as described in "Extremely Low Frequency Plasmas in Metallic Mesostructures", J B Pendry, A J Holden, W J Stewart, I Youngs, Phys Rev Lett, 76, 4773 (1996) which is incorporated herein by reference.

**[0062]** Hence known techniques can be applied to construct the metamaterial required to put the current invention as described above into practice. The materials comprise many unit cells, each of which is designed to have a predetermined value for  $\epsilon'$  and  $\mu'$ , such that they correspond to the values determined by equation (4) above (or for the non-orthogonal case, equation (23) of Annex 1). As will be apparent to the skilled reader, this may involve each unit cell having slightly different values of  $\epsilon'$  and  $\mu'$  to those of its radially neighbouring cells. Each unit cell in the metamaterial acts as a concealing volume element. The concealing volume elements are assembled in the correct respective spatial positions to form the cloaking structure, as calculated by the methods outlined above. The cloaking structure will,



as a result, possess the spatially distributed material parameter values required for electromagnetic concealment of the enclosed volume.

**[0063]** For practical implementation of the theory outlined above, a three dimensional cloaking structure will be necessary in most cases. A solid composite metamaterial structure can be formed using fabrication techniques similar to those used to manufacture a gradient index lens. One such known structure **1000** is shown in FIG. **10**, in which SRR's and wires are deposited on opposite sides lithographically on a standard circuit board to provide a desired material response. This is described in more detail in "Reversing Light with Negative Refraction", J B Pendry, D R Smith, Physics Today, June 2004, which is incorporated herein by reference.

The unit cell structure of the metamaterial used ensures that anisotropy and continuous variation of the parameters, as required by the theoretical solution, can be achieved. Unrelated to cloaking, another application of the transformation theory described above is a device for concentrating fields. FIG. **11** shows a concentrator that concentrates electromagnetic fields incident upon its outer surface (**110**) onto an inner core region (**114**). The transformation that characterizes the concentrator, for the spherical geometry, is shown in FIG. **11**. The outer radius of the device (**110**) is  $R_3$ . A concentrating volume of space (**112**) with radius  $R_2 < R_3$  is compressed to a collecting volume (**114**) of radius  $R_1$ . The shell volume (**116**) that lies between  $R_2$  and  $R_3$  is expanded to fill the region (**118**) between  $R_1$  and  $R_3$ , as FIG. **11** depicts. A simple example of this transformation that compresses the core (**112**) uniformly and stretches the shell region (**116**) with a linear radial function is given by

$$r = \begin{cases} \frac{R_2}{R_1} r' & 0 < r' < R_1 \\ \frac{R_2 - R_1}{R_3 - R_1} R_3 + \frac{R_3 - R_2}{R_3 - R_1} r' & R_1 < r' < R_3 \\ r' & R_3 < r' \end{cases} \quad (12)$$

$$\theta = \theta' \quad (13)$$

$$\phi = \phi'$$

The resulting material properties of permitting and permeability in the concentration device are then

**[0064]**

$$[\epsilon'_{r'}, \epsilon'_{\theta'}, \epsilon'_{\phi'}] = [\mu'_{r'}, \mu'_{\theta'}, \mu'_{\phi'}] \quad (15)$$

$$= \begin{cases} \frac{R_2}{R_1} [1, 1, 1] & 0 < r' < R_1 \\ \frac{R_3 - R_2}{R_3 - R_1} \left[ 1 + \frac{R_2 - R_1}{R_3 - R_2} \frac{R_3}{r'} \right]^2, 1, 1 & R_1 < r' < R_3 \\ [1, 1, 1] & R_3 < r' \end{cases}$$

where the material properties are given relative to the external environment. As with the cloaking structure, the external environment may be free space or any other medium.

**[0065]** In order to concentrate fields into an arbitrarily small volume, we let  $R_1 \rightarrow 0$  and obtain

$$[\epsilon'_{r'}, \epsilon'_{\theta'}, \epsilon'_{\phi'}] = [\mu'_{r'}, \mu'_{\theta'}, \mu'_{\phi'}] \quad (16)$$

$$= \begin{cases} \frac{R_3 - R_2}{R_3} \left[ 1 + \frac{R_3}{R_3 - R_2} \frac{R_2}{r'} \right]^2, 1, 1 & 0 < r' < R_3 \\ [1, 1, 1] & R_3 < r' \end{cases}$$

**[0066]** If we wish the concentration cross section of the sphere to equal it's outer radius, then we let  $R_2 \rightarrow R_3$ .

$$\lim_{R_3 \rightarrow R_3} [\epsilon'_{r'}, \epsilon'_{\theta'}, \epsilon'_{\phi'}] = \lim_{R_3 \rightarrow R_3} [\mu'_{r'}, \mu'_{\theta'}, \mu'_{\phi'}] \quad (17)$$

$$= \begin{cases} [+ \infty, 0, 0] & 0 < r' < R_3 \\ [1, 1, 1] & R_3 < r' \end{cases}$$

**[0067]** This is the perfect field concentrator. The material parameters which are required in the concentrator can be achieved through the use of metamaterials as described in relation to the cloaking structure. The permittivity  $\epsilon$  and permeability  $\mu$  can be controlled independently of one another in each of three dimensions within each unit cell of the metamaterial.

**[0068]** The concentrator device is unique, and different from focusing lenses and mirrors, in that it operates on fields incident from any direction. For electromagnetic sensing or energy harvesting applications, a detector or collector would be placed at the core (**114**) to interact with the intensified fields at that location. Part of the utility of this device is concentration of fields when the direction of their source is initially unknown or constantly changing e.g. solar energy collection or microwave energy beaming on mobile platforms.

**[0069]** A detector placed at the concentrator's core (**114**) could easily be configured to provide accurate directional information as well as collect the energy. This could be accomplished by, for example, using a spherical shaped detector patterned into eight quadrants. By comparing the energy collected from each quadrant, accurate directional information will be obtained. The detector need not be spherical. A transformation could be used that results in a core region that is a thin circular disk. This would make the concentrator compatible with common planar detectors.

**[0070]** The device can also provide impedance matching to the detector. This is achieved by applying the inverse transformation to the desired detector, expanding it from the core radius,  $R_1$ , to the radius  $R_2$ . It is then possible to design an impedance matching layer, (between  $R_1$  and  $R_3$ ), to match the transformed detector to its environment. This impedance matching layer is then transformed with the forward transformation expanding it to fill the region (**118**) between  $R_1$  and  $R_3$ . The resulting shell layer between  $R_1$  and  $R_3$ , provides both concentration and impedance matching functions.

**[0071]** Like the cloak structures the concentrator (**110**) can be perfectly matched to its environment, so that if the fields are not disturbed in the core (**114**) by a detector, the device (**110**) is undetectable by external electromagnetic probing. This device (**110**) can operate in both near and far field regimes and at any size scale and wavelength. The basic

formalism of this transformation can be applied to other basic geometries, (e.g. cylindrical) or applied conformally to an arbitrarily shaped object.

FIG. 12 demonstrates the concentration of rays or field lines from a point source (120) incident upon a sphere (122) radius  $R_3$ , into an inner core region (124) radius  $R_1$ .

[0072] The co-ordinate transfer mapping theory outlined above has been described with respect to diverting the propagation of electromagnetic waves. However it is noted that there is a significant analogy between electromagnetic and other propagating waves such as acoustic waves. In particular, this theory may be applied to obtain specifications for the mechanical properties of a material such as density and stiffness that yield acoustic cloaking. Such a cloak may be used for example to conceal bodies from sonar detection.

[0073] Whilst the description of the cloaking theory above is directed mainly to concealing objects, it will be appreciated that the diversion of electromagnetic disturbances from the cloaked volume into a cloaking shell creates an electromagnetic quiet zone inside. Equation (9) dictates that any electromagnetic radiation produced by an object inside the quiet zone will not be able to emerge from it. This may be put to use in electromagnetic interference shielding applications, for example inside MRI machines. Analogously, acoustic quiet zones may also be achieved.

[0074] The application of the present invention is not limited to the cloaking and concentrator structures as shown in the Figures. As demonstrated clearly in Annex 1, the mathematical solution provided herein applies to cloak a structure of any shape. Furthermore, if a volume is cloaked, an object of any shape or material placed therein will not be detectable by an outside observer, either in reflection mode or transmission mode.

[0075] The methods described herein can be used to apply any appropriate coordinate transformation between any appropriate co-ordinate systems and using any appropriate function of the co-ordinates in the original frame. The cloaking structure used to conceal the material within it can be of any shape or thickness. In particular, the cloaking structure does not have to follow the same shape as the object within that is to be concealed. It will be apparent to the skilled reader that the methods described herein can be used to transform all frequencies of electromagnetic radiation, and for a given application can be applied to radiation in any specific frequency range of the electromagnetic spectrum, including infrared, radio, visible light, x-rays, microwaves and radar.

[0076] In the examples shown impedance matching has been achieved by the ratio

$$\frac{\mu}{\epsilon} = 1.$$

As will be apparent to the skilled reader, impedance matching of the sort described herein can be achieved for

[0077]

$$\frac{\mu}{\epsilon} = m$$

where  $m$  is any real constant value. In particular, the desired ratio of  $\mu/\epsilon$  will depend on the medium in which the cloaking structure is to be embedded.

[0078] While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

What is claimed is:

1. A method of constructing a concealing volume comprising constructing a plurality of concealing volume elements around a concealable volume, each concealing volume element having a material parameter arranged to direct a propagating wave around a concealable volume.

2. A method as claimed in claim 1 in which the material parameter comprises one of refractive index, electrical permittivity, magnetic permeability.

3. A method as claimed in claim 2 in which the propagating wave comprises an electromagnetic wave.

4. A method as claimed in claim 1 in which the material parameter comprises each of electrical permittivity and magnetic permeability.

5. A method as claimed in claim 2 in which the concealing volume is a metamaterial.

6. A method as claimed in claim 5 in which each element comprises at least one of a split ring and a conductive wire providing a respective permeability and permittivity value.

7. A method as claimed in claim 1 in which the concealing volume is designed to divert incoming propagating waves such that outgoing propagating waves appear to be unperturbed to an observer.

8. A method of designing a concealing volume for provision around a concealable volume comprising identifying a co-ordinate transform mapping a concealable volume space onto a concealing volume space and applying a corresponding transform to spatially distributed material parameter values in the concealable volume space.

9. A method as claimed in claim 8 in which the material parameter comprises at least one of the refractive index, electrical permittivity, magnetic permeability.

10. A method of constructing a concealing volume comprising designing a concealing volume as claimed in claim 8, constructing a plurality of elements having said transformed material parameter values and assembling said elements at the respective transformed spatial positions.

11. A method as claimed in claim 10 in which the assembled elements form a metamaterial.

12. A concealing volume for concealing a concealable volume comprising a plurality of concealing volume elements each having a material parameter arranged to divert a propagating wave around a concealable volume.

13. A concealing volume as claimed in claim 12 in which the material parameter is at least one of refractive index, electrical permittivity and magnetic permeability.

14. A concealing volume as claimed in claim 12 in which the concealing volume elements form a metamaterial.

15. A concealing volume as claimed in claim 12 in which each concealing volume element comprises at least one of a split ring and an electrically conductive wire providing a respective magnetic permeability or electrical permittivity value.

16. A concealing volume as claimed in claim 12 further comprising a concealed volume within said concealing volume.

17. A concealing volume as claimed in claim 12 further comprising a plurality of bandwidth enhancing elements.

18. A computer readable medium comprising a set of instructions for implementing a method as claimed in claim 1.

19. A computer configured to operate under the instructions of a computer readable medium as claimed in claim 18.

20. A computer readable medium storing concealing volume element material parameter data derived according to the method of claim 8.

21. A concealing volume as claimed in claim 12 configured for cloaking in at least one of the following electromagnetic spectrum bands: visible, infrared, ultraviolet, x-ray, radio, radar, microwave.

22. A computer readable medium as claimed in claim 18 in which the propagating wave is an acoustic wave and the material parameter comprises at least one of density and stiffness.

23. A method of constructing a concentrator comprising constructing a plurality of concentrator elements to form a concentrating volume and a collecting volume, each concentrator element having a material parameter arranged to direct a propagating wave from the concentrating volume to the collecting volume.

24. A method as claimed in claim 23 in which the material parameter comprises one of refractive index, electrical permittivity, magnetic permeability.

25. A method as claimed in claim 24 in which the propagating wave comprises an electromagnetic wave.

26. A method as claimed in claim 23 in which the material parameter comprises each of electrical permittivity and magnetic permeability.

27. A method as claimed in claim 24 in which the concentrator is a metamaterial.

28. A method as claimed in claim 27 in which each element comprises at least one of a split ring and a conductive wire providing a respective permeability and permittivity value.

29. A method as claimed in claim 23 in which the concentrator is designed to divert incoming propagating waves such that outgoing propagating waves appear to be unperturbed to an observer.

30. A method of designing a concentrator for provision around a concentrating volume comprising identifying a co-ordinate transform mapping the concentrating volume space onto a collecting volume space and applying a corresponding transform to spatially distributed material parameter values in the concentrator space.

31. A method as claimed in claim 30 in which the material parameter comprises at least one of the refractive index, electrical permittivity, magnetic permeability.

32. A method of constructing a concentrator comprising designing a concentrator as claimed in claim 36, constructing a plurality of elements having said transformed material parameter values and assembling said elements at the respective transformed spatial positions.

33. A method as claimed in claim 32 in which the assembled elements form a metamaterial.

34. A concentrator for concentrating a concentrating volume comprising a plurality of concentrator elements each having a material parameter arranged to divert a propagating wave from the concentrating volume to a collecting volume.

35. A concentrator as claimed in claim 34 in which the material parameter is at least one of refractive index, electrical permittivity and magnetic permeability.

36. A concentrator as claimed in claim 34 in which the concentrator elements form a metamaterial.

37. A concentrator as claimed in claim 34 in which each concentrator element comprises at least one of a split ring and an electrically conductive wire providing a respective magnetic permeability or electrical permittivity value.

38. A concentrator as claimed in claim 34 further comprising a collecting volume within said concentrating volume.

39. A concentrator as claimed in claim 34 further comprising a plurality of bandwidth enhancing elements.

40. A computer readable medium comprising a set of instructions for implementing a method as claimed in claim 23.

41. A computer configured to operate under the instructions of a computer readable medium as claimed in claim 40.

42. A computer readable medium storing concentrator element material parameter data derived according to the method of claim 30.

43. A concentrator as claimed in claim 34 configured for concentrating in at least one of the following electromagnetic spectrum bands: visible, infrared, ultraviolet, x-ray, radio, radar, microwave.

44. A method for controlling a propagating wave within a material comprising controlling the values of electrical permittivity and magnetic permeability exhibited by the material independently of one another.

45. A method as claimed in claim 44 in which the material is a metamaterial.

46. A method as claimed in claim 44 in which the propagating wave is an electromagnetic wave.

47. A method as claimed in claim 44 wherein the propagating wave is controlled to circumvent a concealable volume.

48. A method as claimed in claim 44 wherein the propagating wave is directed from a concentrating volume to a collecting volume.

49. A method of defining a spatial distribution of material parameter values of an object comprising performing a spatial coordinate transformation in relation to a volume having a pre-transformation material parameter value spatial distribution, and constructing an object from a metamaterial having a post-transformation material parameter value spatial distribution.

50. A method of defining a spatial distribution of material parameter values of an object comprising performing a spatial coordinate transformation in relation to a volume having a pre-transformation material parameter value spatial

distribution having an effect on a volume surrounding the object, in which the spatial transformation is selected so that the post-transformation material parameter value spatial distribution achieves the same effect on the volume surrounding the object.

**51.** A method as claimed in claim **50** in which the effect on the surrounding volume is non-perturbation of electromagnetic radiation by virtue of presence of the object.

\* \* \* \* \*